THE STRENGTH OF THE EARTH'S CRUST

JOSEPH BARRELL
New Haven, Connecticut

PART VII. VARIATIONS OF STRENGTH WITH DEPTH AS SHOWN BY THE NATURE OF DEPARTURES FROM ISOSTASY

SECTION B, APPLICATIONS OF THE THEORY

GEODETIC EVIDENCE AS TO LIMITING HEIGHTS AND WAVE-LENGTHS

Measurements of strength by maximum loads.—In the course of geologic time the internal forces of igneous intrusion and tangential compression, the external forces of erosion and sedimentation, have tended to strain the crust to its limits of strength, and the degree of isostasy which exists constitutes a measure of those limits. Small loads of large wave-length and large loads of small wave-length will tend to rise to maxima which may be used in connection with the theory of distribution of stress, as considered in Part VII, Section A, to give an approximate idea of the limits and distribution of strength in the crust.

The problem is to find the maximum vertical load and its relation to wave-length acting over areas which may be regarded as

forming roughly a harmonic series. The theory applies best where elongated unit areas are flanked by areas of opposite sign. But even where a single axis of uncompensated elevation or depression is surrounded with a region of mean elevation it may be regarded as a half of a wave sustained by the rigidity of the earth. The stresses in the vertical plane through its crest line would appear to be less than, but not so greatly different from, what they would be for a continued series. Where the load is of oval instead of zonal distribution the stresses would also be somewhat diminished in case the oval is surrounded by a neutral region, but if a series of ovals of opposite signs is analogous to two intersecting wave-series, although the stresses would be complicated and are not in general the sum of the stresses due to the separate series, yet it does not appear that the extreme maxima would be necessarily less than the sum, and many of the maxima would be greater than the maxima of the separate series.

Harmonic loads with short wave-lengths.—Horizontal compression builds mountain folds of which the individual ranges are clearly the results of compression and not of isostatic elevation. Erosion dissects an elevated country on a pattern of a certain scale, deep valleys of erosion separating the crust remnants above base-level which are not yet consumed. These actions produce a surface relief which corresponds roughly to various harmonic series of appreciable amplitude and wave-length, but in this section will be considered only the geodetic evidence of variable mass not isostatically compensated, much of the variation being due to the concealed heterogeneities of density.

The distance between Washington, D.C., and Hoboken, New Jersey, as estimated in Part V, Section B, is 326 km. Within this distance are three intermediate stations and the two limiting stations, each station showing a gravity anomaly opposite in sign to that of the adjacent stations. There must be then at least two wave-lengths. The average change of anomaly between the adjacent stations is 0.021 dyne. As it is wholly improbable that the stations are located at the crest lines of the waves, the whole amplitude may safely be taken as at least 0.026 and the wave-length 160 km.

Seattle and Olympia are 80 km. apart and the difference of their anomalies is 0.126 dyne. If the anomalies had been measured at the points giving maximum values they would certainly give a difference of at least 0.130 or perhaps 0.140, about five times the amplitude of the variations between Washington and Hoboken. This large value seems, however, to be exceptional for the United States and may constitute but a single wave. We may take it, however, as showing that the crust can sustain a harmonic load of 160 km. (100 miles) wave-length and total amplitude of 0.120 dyne. For the reasons explained in Part IV, especially on p. 304, the divisor to be used to turn this anomaly into the equivalence of rock measured in feet could not be over 0.0018 and a better figure for the interpretation of this short wave-length is 0.0015. This gives an amplitude of 8,000 feet (2,440 m.). The part below the mean level is then 50 miles wide and 4,000 feet deep, the adjacent positive parts of the wave being of equal dimensions but in the opposite direction. This is of the same order of relief as the larger ranges of folded mountains and intermontane valleys. The stresses which this harmonic series imposes upon the crust are shown by curve A of Fig. 18.

Maximum loads for mean wave-lengths.—In Part II it was argued that the evidence of anomalies from mountain stations showed regional compensation on the average probably to the outer limit of zone O, radius 166.7 km., diameter consequently 333.4 km.

Over the United States in general the intercepts of the areas of grouped deflections averaged 180 miles. The average diameter would therefore doubtless be as great as 200 miles (320 km.).

On Bowie's map of the New Method gravity anomalies,[1] it is seen that the distances from pronounced maxima to pronounced minima average 250–350 km.

From these several lines of evidence we may conclude with some confidence that the half wave-length for pronounced anomalies in the United States averages near 300–350 km. The wave-length is therefore 600–700 km. (373–435 miles). A wave-length of 600 km. will be taken. The pronounced maxima for these waves runs from plus or minus 0.030 to 0.060 dyne. The real maxima

[1] This article, Part II, *Jour. Geol.*, XXII (1914), 153.

are to be regarded in most cases as situated to one side of the stations and somewhat greater. But exceptional and local maxima must be smoothed out to form a part of the harmonic curve. It is, furthermore, the difference of anomaly between adjacent opposite phases which is the significant feature. This difference runs from 0.060 to 0.080. The latter figure will be chosen. For this wave-length, representing a certain unit area of attraction, the best divisor is perhaps to take 0.0024 dyne of anomaly as equivalent to 100 feet of rock. An anomaly of 0.080 dyne is on that basis equivalent to 3,330 feet (1,015 m.) of rock. The crust of the United States sustains, therefore, harmonic loads 600 km. (373 miles) in wave-length and 1,015 m. (3,330 feet) in total amplitude. The stresses which this wave-series imposes on the crust are shown by curve B, Fig. 18.

Departures from isostasy of large wave-lengths.—For the continent as a whole and in its relations to the ocean basins isostasy is nearly perfect; but the question rises here, how nearly? The first term of the gravity formula for the Vienna system of gravity observations is 978.046 dynes. The first term for the Potsdam system is 978.030. The first term for the United States system after rejecting the Seattle anomalies is, as shown by Bowie, 978.038 dynes. These respective systems differ as a whole by these amounts. We have no right to assume that any one is absolutely correct. The whole of the United States system may lie a little above or below the level giving isostatic compensation with respect to the average surrounding ocean basins, or with respect to the entire earth. The mean value for the United States suggests, however, that, as a whole, the continent lies within a few hundred feet, possibly less than one hundred feet, of the level which would give perfect isostatic equilibrium.

Let us consider next its larger parts. These can be compared with each other and with the United States as a whole. Although, as discussed in Part IV, the map of gravity anomalies lacks detail, the grouping of many stations of like sign into large areas gives confidence in the conclusion that there are regional departures from isostasy. These are of two or three orders of magnitude, of which the areally smaller have been discussed. To bring out the

areally larger we must draw boundaries about large regions which show a dominance of anomalies of one sign. These boundaries, however, must be taken so as to give compact unit areas, so as not to obtain an unreal result by the political expedient of gerrymandering the districts.

Select as a center the point whose geographic co-ordinates are lat. 42°, long. 102°. Describe about this center a circle of 850 km. radius. This includes an area equal to 29 per cent of the area of the United States. It should be taken as including the negative anomaly station 99 on its southern border. This circle covers a large positive region which could be made still more positive by an extension of its boundaries to the northeast over Wisconsin and Michigan. Within this circle are distributed with a fair degree of uniformity 31 of the 122 gravity stations of the United States. The mean with regard to sign of the anomalies of these 31 stations referred to the United States mean with regard to sign is +0.010 dyne. As the mean without regard to sign of all stations in the United States excluding Seattle is only 0.018, it is seen that this positive region stands out clearly from the general average.

West of this circle and, on the south, to the west of long. 107° there are 21 stations, including one of the two Seattle stations. These mark a broad region of negative anomaly. The mean anomaly with regard to sign is −0.017 dyne. There seems to be no reason for completely omitting the exceptionally large Seattle anomalies. One of them has therefore been retained, but if both are omitted the mean is still −0.013. The value of −0.017 will here be adopted. The difference of the means of the central and western regions is consequently 0.027 dyne. Let these be regarded as the positive and negative phases of an harmonic wave and the mean departure of the two phases becomes 0.0135 from each side of the mean plane. Now it may be computed for a harmonic wave represented by the formula $y=A \sin Bx$ that the mean height of the wave above the mid-plane is 64 per cent of the crest height. From mid-plane to crest of this wave-series is therefore 0.021. From the large negative anomalies along the Pacific coast it would seem that this negative zone must extend somewhat further. The wave-length of this series is consequently between

2,600 and 3,000 km. A mean value of 2,800 km. (1,740 miles) will be chosen. From the breadth of half a wave-length it appears that 0.0034 dyne of anomaly may be taken as equivalent to 100 feet of rock. This gives the crest and trough as 625 feet (190 m.) from the mean plane, a total amplitude of 1,250 feet (380 m.). The stress-differences which this wave-series throws upon an earth elastically competent throughout to bear the stresses are shown by curve C, Fig. 18. Helmert has published an extensive paper dealing with the force of gravity and the distribution of mass in the crust of the earth,[1] to which the writer's attention has been called recently by Professor Pierpont, of the mathematical department of Yale University. In this paper Helmert adopts the hypothesis of regional isostasy and finds his results confirmatory of it, but not in accord with the hypothesis of close and local isostatic adjustment. His work is especially valuable as confirmatory of the present conclusions, since it deals with regions outside of the United States. As he does not, however, compute the corrections due to the distant large irregularities of topography, his figures cannot be directly compared with Hayford's New Method anomalies. Nevertheless his conclusions as to the existence of broad regional excesses or defects of mass are comparable to those here reached. Under the section on the horizontal displacement of compensation and extended excesses and defects of mass[2] he sums up part of the evidence in the following statement: "We have then to deal with a continuous region of positive total gravity disturbance in Europe 1,000 km. broad and also with a region of negative disturbance in Asia of at least 500 km. breadth, both possessing great linear extension."

RELATIONS OF ACTUAL STRESSES TO THE SUM OF HARMONIC WAVES

Both Darwin and Love point out that the actual stress-differences imposed by the superposition of different harmonic waves is not in general the sum of the individual stress-differences. Darwin, however, states the special conditions under which the

[1] "Die Schwerkraft und die Massenverteilung der Erde," *Ency. Math. Wissenschaft*, Band VI, 1, B, Heft 2 (1910), pp. 85–177.

[2] *Op. cit.*, pp. 152–54.

resultant is the sum of the individual stress-differences.[1] The three waves which have been considered are types which coexist and are superimposed. The total stress which they give would vary from

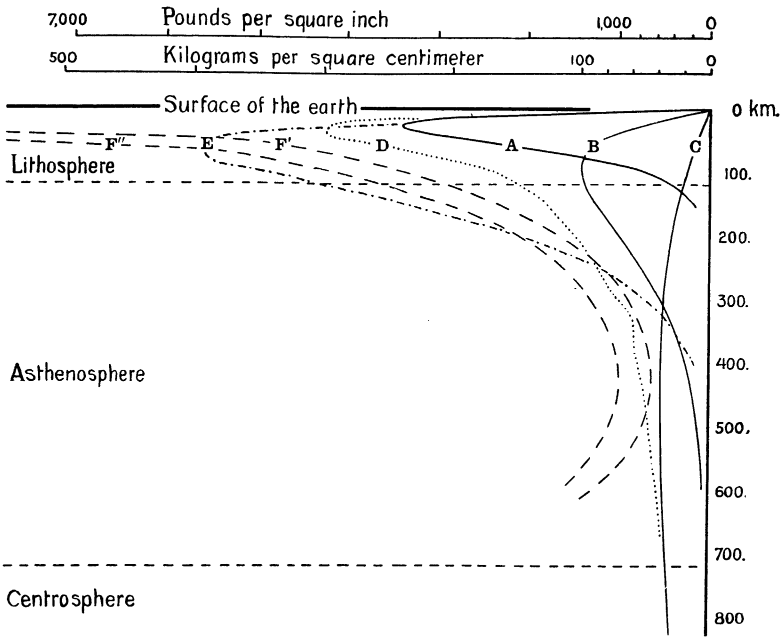

FIG. 18.—Stress-curves for harmonic waves on an earth elastically competent throughout, the waves representing departures from isostasy in the United States as given by analyzing the geodetic data into the following harmonic waves:

A, wave-length 160 km., amplitude 0.120 dyne = 2,440 m. of rock.

B, wave-length 600 km., amplitude 0.080 dyne = 1,015 m., of rock.

C, wave-length 2,800 km., amplitude 0.042 dyne = 380 m. of rock.

D is the sum of A, B, and C.

E, wave-length 400 km., amplitude 0.366 dyne = 4,000 m. of rock (from the Pacific Ocean).

F′, curve of strength suggested by geodetic evidence from the United States.

F″, curve of strength suggested by geologic evidence from various parts of the world.

complete neutralization up to their sum as a possible maximum. Curve D represents such an addition of A, B, and C, Fig. 18. There are reasons why this curve may be taken as a fairer representation of the maximum stress conditions under the United States than

[1] *Scientific Papers*, II, 492.

any individual curve, even though there may be no place where the culminating phases of like sign all coincide and become additive. These reasons are found in the subsurface location of those loads due to outstanding density and also to the added stresses due to isostatic compensation. These causes result in throwing a greater stress upon the outer parts of the lithosphere and also serve to broaden downward the stress diagrams. Furthermore, the stresses due to isostatic compensation of continents would appear to be in reality much greater under the margins than the small values computed by Love,[1] since he has taken the continents as having the broad sweeping surfaces of a harmonic nature, whereas, as a matter of fact, the continents slope off rather abruptly to the depths of the oceans. Facing the Pacific in fact, the two Americas show high mountain elevations. This would cause the stresses in the vicinity of these continental margins to resemble those imposed by a great mountain chain and its isostatic compensation rather than those imposed by the breadth of a continent. If isostatic compensation is complete under mountain slopes, Love shows for the cases computed by him that the maximum stress is about equal to that given by a column of rock one-fourth the total height from mountain crest to valley bottom. If the abyssal slopes of the continental platforms be taken as averaging 3–4 km. in elevation and 50–100 km. in width, it is seen that, even if fully compensated, they add stresses to the crust which may approach in magnitude one-half of the stresses shown by curve A of Fig. 18. The extreme depths of slope are much greater and it is clear that isostatic compensation cannot be exact under these great reliefs. Therefore we may conclude that curve D does not overestimate the maximum stresses imposed by the irregularities of the crust, both compensated and uncompensated, as indicated by geodetic evidence within the United States and especially along its ocean borders. This investigation, however, has been of a general nature and is designed merely to establish an order of magnitude. It remains for future work to make more precise analyses for each locality from the data which may be acquired, and especially to investigate quantitatively the problems offered by critical areas.

[1] Some Problems of Geodynamics (1911), chap. ii.

GEOLOGIC SUGGESTIONS AS TO MAGNITUDES OF CRUSTAL STRESSES

Submarine geanticlines and geosynclines.—Here will be considered some geologic illustrations of departures from isostasy, arranged in order of harmonic wave-length. They are to be compared with the results obtained from the study of the geodetic data. Most of the geologic evidence is merely suggestive, not conclusive, since diametrically opposite opinions are held as to the probability of the visible load being offset by an invisible compensation. As suggestions, however, they are none the less valuable, and point the way to needed geodetic observations.

The mountain folds advance from Asia over the floor of the Pacific Ocean, forming the system named by Suess the Oceanides. Mostly hidden beneath the ocean surface, they have been but little affected by erosion. Their ridges and deeps mark the greatest mountain reliefs of the globe. It is probable that here, if anywhere, tangential pressures have forced the crust into folds whose height combined with span is as great as the strength of the crust can endure. To what degree the elevations and depressions are compensated is, however, unknown, and the great arches are supported in part by the lateral pressure of the ocean water. It is quite possible if not probable that appreciable changes of deep-seated density may accompany the growth of such ridges, especially as they mostly exhibit a volcanic activity and are to a greater or less extent structures built up by igneous extrusion. It is not at all probable, however, that they are completely or possibly even largely compensated, but where the mountain folds and trough-like deeps broaden into plateaus or anti-plateaus the presumption is strengthened that the forms may there be isostatically compensated to a large degree. Such plateaus or anti-plateaus cannot then be used in the present argument. The ridges and troughs, however, show in their forms, as has been stated, modes of construction which are not conditioned on isostasy. Let attention be turned then to the folds of the ocean floor.

Passing from west to east, first may be noted between the Philippines, Borneo, and New Guinea a complex of ridges and basin-like deeps. The larger wave-length of that region runs from 300 to 500 km. The Ladrone Islands and Nero Deep give a

distance of about 150 km. from crest to trough and a wave-length of 400–500 km., these folds and many others exhibiting a lack of symmetry. The existence of strong folding pressures and a tendency to overthrusting and secondary vertical faulting seem to be expressed therein. The great fold passing north from New Zealand and showing as the Kermadec and Tonga islands with their fore-deeps gives a distance from crest to trough of 120–180 km., a wave-length of 400–500 km. Lower California and the troughs on each side show a wave-length of 350 km. The region of the Lesser Antilles is tectonically a northward branching of the Andean mountain system and shows, like the folds of the Pacific, crustal undulations with a wave-length of 350 km. We may conclude then that these folds of the ocean floor have a marked tendency to a wave-length of 300–500 km., there being commonly one great asymmetric fold passing out into subordinate marginal folds. The volcanic chain of the Hawaiian Islands shows, however, no related deeps and has a half wave-length of about 200 km.

Hayford and Bowie have given the New Method anomalies for a few stations in these regions.[1] A portion of the data has been abstracted and given in Part IV of the present article.[2] Four observations of Hecker's for the Tonga Plateau and Tonga Deep are given. They may not be of high value, since the method has been criticized as not possessing accuracy comparable to observations made by pendulum upon land. Furthermore, the four observations, two over the plateau and two over the deep, are spread through a distance of 5,100 km. along the axis of the structure instead of being taken on a transverse section. Nevertheless, as the reliefs and the corresponding anomalies are all of great magnitude, the errors become relatively small and the mean of the observations is therefore of some value. The two New Method anomalies for the Tonga Plateau give a mean of +0.202 dyne, the depth of water being 2,700 m. The two New Method anomalies for the Tonga Deep give a mean of −0.172 dyne, the depth of water averaging 7,500 m. If the amplitude

[1] *The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity*, 1912, p. 81.

[2] *Jour. Geol.*, XXII (1914), 311.

of the uncompensated portion of the crust-waves be measured in terms of anomaly by taking the algebraic sum of the anomalies over the plateau and the deep, a total amplitude is obtained of 0.374 or a half-amplitude of 0.187. On the island of Hawaii an observation on Mauna Kea at an elevation of 3,981 m. gave a New Method anomaly of +0.183, almost the same figure as the half-amplitude for the great Tonga crust-wave.

Helmert has discussed the gravity disturbances found in the Hawaiian Islands and states of them: "For the Hawaiian Islands it must be concluded on the whole that a part of the mass gives rise to positive gravity disturbances and only the remainder is isostatically supported. If the disturbances were produced solely by the mass of the islands the values of Δg and $\Delta g''$ [the disturbances of gravity] would be somewhat greater than they are found."[1]

From this review of the mountain chains of the Pacific it may be concluded that the ocean floor can sustain a harmonic wave-length of 400 km. which gives an anomaly at the crest lines as great as that observed on Mauna Kea, 0.183 dyne. To interpret this as an equivalent load of rock a divisor must be selected. The divisor depends upon the depth and distribution of compensation and the area of the region of outstanding mass. As shown in Part IV, p. 311, 0.0024 dyne might reasonably be chosen as the amount of anomaly equivalent to 100 feet of rock, but for these great loads it is desirable to lean toward the side of an underestimate. Therefore 0.0030 will be taken as the divisor. This gives 1,868 m. as the crest height of the uncompensated portion of the Hawaiian mountain chain. The same applies to the Tonga fold. If, however, 0.0024 should be chosen as the divisor, then 0.183 dyne of anomaly would correspond to a half-amplitude of 2,334 m.

It may be taken then as fairly certain that these great mountain chains show reliefs which depart as much as 2,000 m. above and below the mean level which would give perfect isostasy. It may be concluded in consequence that the oceanic crust can sustain a harmonic wave-length of 400 km. with an uncompensated amplitude measured by 4,000 m. of rock. The diagram of

[1] "Die Schwerkraft und die Massenverteilung der Erde," *Ency. math. Wissenschaften*, Band VI, 1, B, Heft 2, (1910), p. 133.

stress-differences for this is shown in curve E, Fig. 18. But if the rock has a density of 2.67 and the sea-water a density of 1.03, this corresponds to an amplitude beneath the ocean surface of 6,513 m. of uncompensated rock. This is only about two-thirds of the maximum relief which is observed, so that it is well within the limits of possibility. These few available figures suggest that the sharp submarine ridges and deeps may not be more than one-third or two-thirds compensated.

The Niger delta.—Reverting to the discussion of the Niger delta given in Part I, it is seen that there is no evidence of depression around its margin. It may be taken then as the positive half of a harmonic wave well within the limits of crustal strength. If the section of the delta be taken as given in Figs. 3 and 4, pp. 31, 43, it is seen that the load is disk-like in form, instead of being indefinitely elongated at right angles to the section in accordance with the form of a zonal harmonic. It seems likely, because of these two departures from the nature of a harmonic series, that the stresses beneath it are not more than half of those which would be given by the completed harmonic curve. As it is merely the order of magnitude of the stress-differences which we may hope to attain we may proceed in accordance with these rough assumptions. It is seen that the section of the delta shows a half wave-length of about 300 km. and a maximum thickness equivalent to 1,650 m. of rock upon land. This corresponds to the half-amplitude or thickness above the mean plane. If half of this is taken as a measure of the stress, it gives a wave-length of 600 km. and a total amplitude of 1,650 m. The stress-curve for this harmonic series is 60 per cent larger than the stresses due to the outstanding masses of the same wave-length as given by the geodetic evidence in the United States and shown in curve B, Fig. 18. As the estimate from the Niger delta is very imperfect and unchecked by pendulum observations reduced by the New Method, the stress-curve is not plotted.

The existing continental ice sheets.—Two ice sheets of sub-continental proportions remain in existence, the Greenland and Antarctic. They form great plateaus sloping upward from the margins; the Greenland sheet reaching elevations at its center

between 9,000 and 10,000 feet, the Antarctic attaining to about 11,000 feet. The average thickness of the ice must be thousands of feet in each case. The development of these ice caps during the refrigeration of climate which marked the later Tertiary must have imposed upon the crust great loads of wide span. If isostatic equilibrium was previously complete to a large degree, the ice mantles should give valuable measures of crustal strength. For this purpose, however, a set of gravity measurements should be carried inland and reduced by the Hayfordian method. The facts that these two ice-mantled areas are both high plateaus, and that no other adjacent unglaciated land is of similar topographic character, suggest that these regions may be competent to carry great thicknesses of ice without isostatic yielding. There is no present basis, however, for making a quantitative estimate. It must be borne in mind, furthermore, that the ice mantle is only about one-third of the density of rock and that lofty mountains exist in both regions, showing that these lands would possess considerable mean elevation even without the presence of the ice. The effect of the difference of density between ice and rock may be appreciated by considering that an ice sheet 3,000 feet in thickness would possess the same mass as a layer of rock 1,000 feet thick. For isostasy to remain perfect after the development of this ice sheet, the crust would have to sink 1,000 feet, but the surface of the ice would still be 2,000 feet above the former level and give an appearance of load which would not in reality exist.

This is a problem meriting research for several reasons. A knowledge of the load which is sustained by these regions would show to what degree the warpings connected with the extinct Pleistocene ice sheets were mere elastic responses to load, to what degree they marked subcrustal plastic flow working toward isostasy. The results could be applied also to the problem as to how far from isostatic equilibrium a continent might come to lie as a result of continent-wide base-leveling in a period of geologic quiet. It seems not impossible that the stress-curve due to the portion of the glacial load which is elastically sustained would give stress-differences greater at a depth of 300–500 km. than those shown by curve C, Fig. 18. Such an investigation may then

be an essential factor in measuring the maximum strength of the lithosphere and more especially the asthenosphere.

Accordance of geologic with geodetic evidence.—The United States and its bordering ocean bottoms is a region of moderate reliefs as compared to the great folds of the ocean floor or of the continent of Eurasia. The geologic forces of folding and uplift have not worked here with their greatest intensity and the central and eastern half of the continent has been affected by the world-involving Cenozoic diastrophism to only a moderate degree. It is to be expected then that the greatest strains upon the crust, the maximum departures from isostasy, would not be found here. In accordance with this expectation it has been seen that by far the greatest New Method gravity anomalies are found in other regions and associated in most cases with the greater reliefs of the globe. The geologic evidence is in harmony; the amount of uncompensated relief, parallel to the geodetic evidence, is greatest for the lesser wave-lengths; but, throughout, the geologic evidence suggests that the actual burdens which can be borne by the crust, as found in regions of culminating stress, are appreciably greater than those detected by geodetic methods as existing in the region of the United States.

If, in some past ages, as during the Appalachian or Sierran revolutions, strains were generated in this continent as great as those found now in some other regions, it would appear that the slow changes of geologic time, of erosion and crustal readjustment, have partially eased the crust of its load. We may have, then, a variable crustal strength—a maximum strength exhibited during and following the crises of great diastrophism; another, lesser strength, which measures the loads which the crust without failing can bear through all of geologic time.

ADJUSTMENT OF LOADS TO THE DISTRIBUTION OF STRENGTH

It has been seen that the departures from flotational equilibrium may become very notable and are of greatest vertical magnitude for wave-lengths from 100 up to 400 km. The strains generated by these loads, if distributed through an elastic crust,consequently

reach maximum values at depths not exceeding 64 km. Is this because the earth shell below the zone of compensation is strong, but for some unrelated reason free from large stress-differences, or is there an absence of such stress-differences because this shell is too weak to bear them? If the latter is true, then the relations of amplitude to wave-length which have been developed in this chapter offer additional proofs of the reality of the existence of the asthenosphere.

The geologic evidence on the evolution of continental structures and elevations leads to the conclusion that the distribution of stress-differences must be in reality the result of the existence of a zone which cannot carry large distortional strains, as may be seen upon brief consideration.

The internal activities of igneous intrusion and of tangential compression do not in themselves work toward isostatic equilibrium, but merely toward accentuation of relief. Erosion and sedimentation, while tending to destroy this relief, are not agents tending to create, but to destroy, such isostatic relations as have developed. All of these activities work on a continental or subcontinental as well as on an orogenic scale, as seen in the Cenozoic history of the broad Cordilleran province, yet while the orogenic departures from isostasy are vertically very great, the continental departures are very moderate. For the latter there must be then some more narrowly limiting condition. This corresponds to the incapacity of a deep zone, the asthenosphere, to carry large stress-differences and the incapacity of the lithosphere in spite of its greater strength to act effectively after the fashion of a beam for loads of great span. The orogenic structures, on the other hand, give maximum stresses much nearer the surface, in the stronger lithosphere; because of their shorter wave-lengths they do not produce in it bending stress as in a loaded beam and affect comparatively little the deeper-seated asthenosphere.

If, then, it is known from the preceding theoretical considerations that the limits of strength of the lithosphere and asthenosphere determine the limits of the departures from isostasy, the analysis of the nature of these departures may lead in turn to a knowledge of the distribution of strength.

CHARACTER OF THE CURVE OF STRENGTH

In curve F′ of Fig. 18 is shown the nature of the curve of strength as suggested by the geodetic evidence from the United States. In curve F″ is shown the nature of the curve as suggested by the departures from isostasy exhibited by the great mountain axes and possibly by the continental ice sheets. These curves may be taken as showing the value of the elastic limit at various depths for permanent stresses. With varying geologic conditions, especially those connected with rising magmas and their emanations, the curve of strength must vary widely, and furthermore no very close parallelism of strength-curve and stress-curve is to be expected. These curves, therefore, are intended to bring out general relations; they are of qualitative, not quantitative value. The drawing of curve F″ somewhat inside of curve E means that below the point of maximum stress in E, as given for a homogeneous elastic earth, the stress is assumed as somewhat greater than the crust at those levels can sustain. Upon the development of this load plastic flow in these deeper levels would take place maintaining the stress within the strength curve for each level; the crust above would come to act to some extent as a bending plate, the stresses within it would increase, chiefly within the upper and lower portions. This added strain would compensate for the yielding below. For the reasons discussed previously, however, showing the structural weakness of the lithosphere as a beam, this action, it is thought, could not go very far, and, in consequence, the loads on the lithosphere are essentially such as to give stresses contained within it, distributed according to Darwin's law. The preceding deals only with that part of the curve of strength which marks the gradation from lithosphere to centrosphere. The relations of this part to those above and below need still to be considered.

The highest stress found for the loads regarded as harmonic waves was for the great folds on the floor of the Pacific Ocean. These were taken as equivalent to harmonic waves of rock of density 2.67, 400 km. in wave-length, and 4,000 m. in amplitude. But even these folds give a maximum stress of only 393 kg. per sq. cm. (5,590 pounds per square inch), and this at a depth of 64 km. At the surface strong limestone or granite can

sustain a stress-difference of 1,750 kg. per sq. cm. (25,000 pounds per square inch), and selected specimens show ultimate breaking strength approaching 2,800 kg. per sq. cm. For stresses of geologic endurance and in the heterogeneous outer crust it is probable, however, that stress limits should be chosen below 1,750 kg. per sq. cm.

The work of Adams and King has shown that small cavities in granite are not closed when the rock is subjected to the pressure and temperature normally existing in the earth at a depth of 11 miles.[1] The presence of occluded gases acting through great lengths of time, by facilitating recrystallization, might affect this result of laboratory experiments, but the capacity of dry rock to sustain even greater cubic pressures without yielding seems to make safe the conclusion that except in the presence of magmatic emanations the crust at a depth of 11 miles (17.7 km.) is able to bear a stress difference of 100,000 pounds per square inch and is at least four times as strong as rock close to the surface.

At twice this depth, however, the temperatures become such that if it were not for the great pressures even dry rocks would approach a molten condition. The presence of high temperatures and of gases which may act as crystallizers presumably becomes dominant at such depths over the effects of the increasing pressures. We many conclude, therefore, that the maximum strength of the crust in regions free from igneous activity is found at levels above rather than below 40 km. and may lie between 20 and 30 km. deep.

To bring to a focus this discussion a tabulation of ratios of strengths for increasing depths may be given, as derived from the strength curves F′, F″ of Fig. 18, the standard being taken as the strength of surface rocks. By giving them merely as ratios and stating that the average strength of the solid rocks at the surface is itself an uncertain quantity owing to complications of structure and composition, the appearance of an undue certainty is avoided.

The general conclusion which stands out from this tabulation is that the weakest part of the asthenosphere is of the order of one one-hundredth of the maximum strength of the lithosphere and is perhaps only a twenty-fifth of that of massive surface rocks. Its

[1] *Jour. Geol.*, XX (1912), 97–138.

limit of capacity for sustaining stress-differences is apparently of the order of 1,000 pounds per square inch, though its weakness may be masked to some extent by the strength above. From the evidence, however, it seems capable of carrying stresses of more than 100 pounds per square inch, but is clearly incapable of carrying stresses of as much as 5,000 pounds per square inch. To reach a

TABLE XXX

ESTIMATED APPROXIMATE RATIOS GIVING THE VARIATION OF STRENGTH WITH DEPTH AS SHOWN BY THE NATURE OF DEPARTURES FROM ISOSTASY

LITHOSPHERE

Depth in Kilometers	Strength in Percentage
0	100
20	400
25	500
30	400
50	25
100	17

ASTHENOSPHERE

Depth in Kilometers	Strength in Percentage
200	8
300	5
400	4

more definite conclusion the subject must be tested from many angles and is a problem for the geophysicist rather than for the geologist, but the results are of geological importance and the geologic and geodetic data may turn out to have more determinative value on the distribution of strength than the evidence from tides and earthquakes.

[*To be continued*]